Spectral Analysis of Heart Sounds Associated With Coronary Occlusions

Dominique Gauthier, Yasemin M Akay, Robert G Paden, William Pavlicek, F. David Fortuin, John K Sweeney, Richard W Lee and Metin Akay, *Senior Member, IEEE*

***Abstract*— Numerous studies based on the spectral analysis of diastolic sounds showed an increase in the high frequency portion of the spectrum for patients with coronary artery disease (CAD) compared with normal patients. The overall goal of this study is to detect the presence of coronary artery disease in patients using a noninvasive and inexpensive approach. A commercially available electronic stethoscope was used to record the diastolic heart sounds from patients diagnosed with or without CAD based on their coronary angiography examination. The Fast Fourier Transform, a widely used signal processing method, was then implemented on the diastolic segments. The power ratios of the energy above 130 Hz to the energy below 130 Hz were calculated for normal and abnormal patients and compared. Results furthermore confirmed that patients with CAD have more energy in the higher portion of their spectrum, resulting in higher power ratios than for normal patients ($p < 0.05$). This approach led to a sensitivity of 71%, a specificity of 83% and an overall accuracy of 73.3% using an optimal threshold ratio of 1.5. These results suggest that the proposed system could be used in clinics as part of standard physical examinations.**

***Index Terms*—Coronary artery disease, Fast Fourier Transform, occlusions, power ratio, spectral energy.**

I. INTRODUCTION

ISCHEMIC heart disease is the most common cause of death in Western culture, accounting for about 35 percent of all deaths in the United States [1]. Ischemia results from insufficient coronary blood flow, which is most frequently caused by atherosclerosis. The continuous accumulation of plaque causes the narrowing of coronary arteries, a condition known as coronary artery disease (CAD). CAD affects about 13 million Americans and causes the death of more than half a million people each year [2].

Coronary angiography is the gold standard used for the detection of coronary artery disease. Although considered the most reliable technique, it is nonetheless expensive, invasive, time consuming and presents some risks for the patient [3]. The development of a reliable, simple and inexpensive method that is also noninvasive would enhance the ability to detect coronary stenosis in its early stages, prevent its associated complications and be useful as a monitoring procedure for patients undergoing coronary artery disease treatment [4]-[23].

As early as the late sixties, cases of diastolic murmur caused by poststenotic turbulent blood flow in coronary arteries were reported [9]-[13]. Following studies furthermore indicated that partial occlusions of the coronary arteries produce sounds due to the turbulence of the blood flow [4]-[23]. Since the coronary blood flow is maximum during diastole [1]-[29], the sounds related to turbulent flow should be detectable during this period. It has been shown that the diastolic segments of the cardiac cycle contain useful information for the detection of CAD. In fact, numerous studies based on the spectral analysis of diastolic sounds showed an increase in the high frequency portion of the spectrum for patients with CAD compared with normal patients [4]-[8], [21]-[23], [26]-[29].

The overall goal of this research is to detect the presence of coronary artery disease in patients using a noninvasive, passive, quick and inexpensive approach that could eventually be implemented as part of the standard medical examination routine. In this objective, an inexpensive and commercially available electronic stethoscope was used to record the diastolic heart sounds from patients diagnosed with or without CAD based on their coronary angiography examination. The diastolic sounds were then further processed using Matlab. The Fast Fourier Transform, a widely used signal processing method, was then implemented on the diastolic segments. The power ratios of the energy above 130 Hz to the energy below 130 Hz were calculated for normal and abnormal patients and compared.

II. METHODS

The heart sounds from 34 normal or abnormal patients were recorded before and after angiography using an electronic stethoscope (Thinklabs ds32a). Patients were selected from those undergoing catheterization at Mayo Clinic Scottsdale. Recordings were performed at Mayo in compliance with IRB informed consent The amplification factor of the stethoscope was set to its maximum (x50) during the recordings and the Bell recording mode was used. The stethoscope was placed on the patient's chest, at the fourth intercostal space and about 10 centimeters to the left of the midline of the sternum. Once in position, it was held in place by its own weight in order to

D. Gauthier, Dr. Y. Akay and Dr. M. Akay are with the Biomedical Engineering Departement, Arizona State University, Tempe, AZ 85281 USA (e-mail: metin.akay@asu.edu).

Dr. W. Pavlicek and F. D. Fortuin, M.D., are with Mayo Clinic, Scottsdale, AZ 85259 USA.

All the correspondence should be made to Dr. Metin Akay by e-mail at metin.akay@asu.edu.

978-1-4244-1868-8/08/$25.00 ©2008 IEEE.

reduce motion artifacts related to manipulation.

During the recordings, patients were asked to hold a half breath for about 3 periods of 10 seconds. The recordings of 4 patients were excluded from the study, 1 due to mitral regurgitation and 3 others due to a prior history of bypass surgery grafting. For each patient, 15 successive diastolic segments were randomly selected from a recording. Segments with heavy 60 Hz contamination, lung sounds or ambient noise were excluded from further analysis. Also, for one of the remaining 30 patients (patient #4), only 12 segments were extracted due to the limited number of cardiac cycles recorded.

Each diastolic segment had a length of 128 ms and was extracted starting 100 ms after the second heart sound. This period was selected since it coincides with the maximum coronary blood flow. All recordings were sampled at a rate of 4 kHz.

The RMS value of each segment was calculated in the time domain. Signals were normalized according to this value in order to account for sound attenuation effects due to physical differences between patients, such as chest mass and size.

Segments were then filtered between 60 and 500 Hz in order to reduce 60 Hz noise and since the amount of energy above 500 Hz was negligible. The bandpass filter used was a Butterworth filter of order 5.

The FFT spectrum of each segment was then calculated over 512 samples, as follows:

$$X[k]=\sum_{n=0}^{N-1} x[n]e^{-j\frac{2\pi kn}{N}} \tag{1}$$

where x[n] is the segment in the time domain, n represents each sample and N is the total number of samples. In the frequency domain, k represents the sample frequency.

The average FFT of the 15 segments was then calculated for each patient. The amount of energy between 80 and 130 Hz as well as between 130 and 300 Hz were calculated for each average FFT using the area under the curve over each frequency range. These frequency ranges were selected based on the differences observed between the spectra of normal and abnormal patients. The ratio of these amounts of energy was calculated as follows for each patient:

$$Ratio=\frac{Energy\ above\ 130Hz}{Energy\ below\ 130Hz} \tag{2}$$

III. Results

Fig. 1 illustrates the average FFT spectrum of all normal and abnormal patients included in this study. On average, the diastolic segments recorded from the abnormal patients have more energy components in the range of 130-300 Hz than is the case for normal patients. Using the average FFT spectrum for all normal and abnormal patients, the average amount of spectral energy found between 80-130 Hz and 130-300 Hz and the power ratio with the standard error (±SE) were calculated for each category, as shown in Table I.

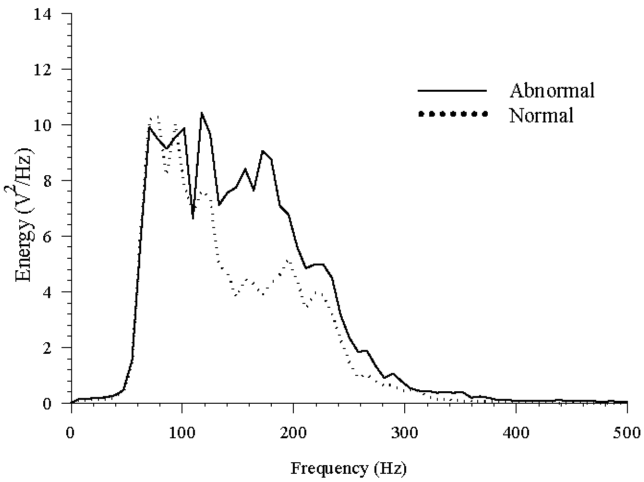

Fig. 1. Average FFT spectrum of all normal and abnormal patients included in the study. Dotted line: average spectrum of all normal patients; solid line: average spectrum of all abnormal patients.

TABLE I
Average Energy for All Normal/Abnormal Patients

Condition	Average Energy 80-130 Hz ± SE (V^2/Hz)	Average Energy 130-300 Hz ± SE (V^2/Hz)	Average Power Ratio ± SE
Normal	58.20 ± 7.96	74.53 ± 9.81	1.36 ± 0.19
Abnormal	64.71 ± 3.19	117.96 ± 7.31	1.88 ± 0.12

On average, higher ratio values were obtained for abnormal patients than for normal patients due to an increase in the amount of energy found in the 130-300 Hz range. The t-test showed that the difference between the mean power ratios obtained for normal and abnormal patients were significantly different ($p<0.05$).

By choosing the optimal threshold detection ratio as 1.5, a sensitivity of 71% and a specificity of 83% were obtained, i.e. 17 out of 24 abnormal patients and 5 out of 6 normal patients were correctly detected. However, patients #4, 5, 10, 11, 20, 23, 24 and 26 were misdiagnosed. This leads to an overall detection rate of 73.3%, i.e. 22 out of 30 patients correctly detected.

Considering the misdiagnosed abnormal patients (#4, 5, 11, 20, 23, 24 and 26), there is no clear trend between them except the fact that they all presented one severe occlusion either in their LAD or RCA. In fact, 4 out of the 7 misdiagnosed abnormal patients had 85%+ occlusion of the LAD, 1 patient had 2 occlusions in the LAD (50 and 70%) and a 99% occlusion of the RCA, while the 2 remaining patients had 100% occlusion of the RCA. Severe occlusions above 85% have been shown to limit the blood flow and that the sound can thus be expected to appear normal [27]. However, since 6 of these 7 patients also had other occlusions of a lesser degree in other coronary arteries.

IV. Discussion

We suppose that patients' health history and obesity level could be responsible for these misdiagnoses. The mass and nature of chest tissue is related to the sex and obesity level of the patient and may have attenuated sound transmission through the chest, making it more difficult to detect turbulent flow. In addition, patients' smoking habits, age, sex and blood pressure may have influenced these results. The status of the circulatory system, including blood pressure, is related to age, smoking habits and the health history of the patient, and may have modified the nature of the turbulent flow in the coronary arteries.

Also, the size of the coronary arteries and the percentage of occlusion may have changed the characteristics of the sound generated by the turbulence. The anatomical location of the coronary arteries relative to the position of the stethoscope on the chest wall may have affected the ability to record the sound in some patients and may have induced some variations between them. The proximity between the stethoscope and the occlusion is a key factor that is furthermore influenced by the residual amount of air in the patient's lungs during the recordings. Also, the curvature of the chest wall may have caused the stethoscope not to be completely sealed to provide the best contact against the skin, therefore not allowing for optimal displacement of the stethoscope diaphragm upon reception of the acoustic waves and allowing external noise to be captured.

Overall, our results furthermore confirm the previous findings [4]-[23] and show the usability of the electronic stethoscope in clinics. We believe that this method will have an impact since it is based on an inexpensive, noninvasive, quick and passive approach.

V. Conclusion

This study demonstrated the detection of patients with CAD from patients without CAD based on the analysis of their energy spectrum using a simple, noninvasive and inexpensive approach. This project furthermore encourages the development of a method that could eventually be implemented as part of routine physical examinations and permit mass screening of CAD in the doctor's office, therefore preventing its associated complications and significantly improving the health of the population in Western countries.

Acknowledgment

The author would like to thank Dr. Selçuk Çömlekçi of the Biomedical Engineering Department at ASU as well as Robert Paden, Dr. Kwan Lee and Dr. Daniel Ng of Mayo Clinic Scottsdale for their collaboration to the data collection process.

References

[1] A. Guyton, J. Hall, *Textbook of Medical Physiology*, 11th edition, Elsevier-Saunders, 2006.

[2] National Heart, Lung, and Blood Institute. (2006). *Disease and Condition Index.* Available: http://www.nhlbi.nih.gov/health/dci/index.html

[3] M. A. Krupp, *Current Medial Diagnosis and Treatment.* Los Altos, CA: Lange Med. Publ., 1982.

[4] J. Semmlow, W. Welkowitz, J. Kostis, and J. W. Mackenzie, "Coronary artery disease-correlates between diastolic auditory characteristics and coronary artery stenoses," *IEEE Trans. Biomed. Eng.*, vol. BME-30, no. 2, pp. 136-139, Feb. 1983.

[5] M. Akay, J. L. Semmlow, W. Welkowitz, M. Bauer, J. Kostis, "AR modeling of diastolic heart sounds," *Proc. IEEE EMBS Frontiers in Medicine*, New Orleans, 1988.

[6] M. Akay, J. L. Semmlow, W. Welkowitz, J. Kostis, "Parametric modeling of diastolic heart sounds before and after angioplasty," *Proc. IEEE EMBS Frontiers in Medicine,* Seattle, 1989.

[7] J. Semmlow, M. Akay, W. Welkowitz, "Noninvasive detection of coronary artery disease using parametric spectral analysis methods," *IEEE Engr. Med. Biol. Mag.,* vol. 9, pp. 33–36, 1990.

[8] M. Akay, J. Semmlow, W. Welkowitz, M. Bauer, J. Kostis, "Noninvasive detection of coronary stenosis before and after angioplasty using eigen vector methods," *IEEE Trans. Biomed. Eng.,* vol. 37, pp. 1095–1104, 1990.

[9] W. Dock and S. Zoneraich, "A diastolic murmur arising in a stenosed coronary artery," *Amer. J. Med.,* vol. 42, pp. 617-619, 1967.

[10] P. G. Lund-Larsen, "Coronary artery stenosis murmur. A case report," *Acta Med. Scand.,* vol. 182, pp. 433-435, 1967.

[11] J. F. Sangster and C. M. Oakley, "Diastolic murmur of coronary artery stenosis," *Brit. Heart J.,* vol. 35, pp. 840-844, 1973.

[12] T. O. Cheng, "Diastolic murmur caused by coronary artery stenosis," *Ann. Int. Med.,* vol. 72, pp. 543-546, 1970.

[13] J. R. Berg, K. A. Weaver, T. Russell, and D. G. Kassenbaum, "Disappearance of coronary artery stenosis murmur after aorta-coronary by-pass," *Chest,* vol. 63, p. 440, 1973.

[14] T. O. Cheng, "Physical diagnosis of coronary artery disease," *Amer. Heart J.,* vol. 80, pp. 716-719, 1970.

[15] G. W. Duncan, J. O. Gruber, C. F. Dervey, G. S. Myers, and R. S. Lees, "Evaluation of carotid stenosis by phonoangiography," *New Eng. J. Med.,* vol. 27, pp. 1124-1128, 1975.

[16] M. M. Kartchner, L. P. McRae, F. D. Morrison, "Noninvasive detection and evaluation of carotid occlusive disease," *Arch. Surg.,* vol. 106, pp. 528-535, 1973.

[17] R. S. Lees, G. S. Myers, "Noninvasive diagnosis of arterial disease," *Adv. Intern.,* vol. 24, pp.475-508, 1982.

[18] R. M. Rosen, S. P. Parthasarathy, A. F. Turner, D. H. Blakenhorn, E. J. Roschke, "Phonoangiography by autocorrelation," *Circulation,* vol. 55, pp. 626-633, 1978.

[19] J. Roffman and A. Fieldman, "Coronary bypass graft stenosis causing diastolic murmur in patient on hemodialysis" (letter), *Chest,* vol. 78, pp. 356-357, 1980.

[20] I. Guler, M. K. Kiymik, N. F. Guler, "Order determination in autoregressive modeling of diastolic heart sounds," *J. Med. Syst.,* vol. 20, pp. 11–17, 1996.

[21] M. Akay, W. Welkowitz, J. L. Semmlow, J. Kostis, "Application of the ARMA method to acoustic detection of coronary artery disease," *Med. Biol. Eng. Comput.,* vol. 29, pp. 365–72, 1991.

[22] M. Akay, Y. Akay, W. Welkowitz, J. Semmlow, J. Kostis, "Application of adaptive filters to noninvasive acoustical detection of coronary occlusions before and after angioplasty," *IEEE Trans. Biomed. Eng.,* vol. 39, pp. 176–84, 1992.

[23] Y. Akay, M. Akay, W. Welkowitz, J. Semmlow, J. Kostis, "Noninvasive acoustical detection of coronary artery disease: a comparative study of signal processing methods," *IEEE Trans. Biomed. Eng.,* vol. 40, pp. 571–578, 1993.

[24] R. A. Olsson and W. J. Bugni, "The coronary circulation," in *The Heart and Cardiovascular System: Scientific Foundations,* New York: Raven Press Publishers, 1986, pp.987-1037.

[25] H. S. Lowensohn, E. M. Khouri, D. E. Gregg, R. L. Pyle, R. E. Patterson, "Phasic right coronary artery blood flow in conscious dogs with normal and elevated right ventricular pressures," *Circ. Res.,* vol.

39, no. 6, pp. 760-766, 1976.
[26] O. Tateishi, “Clinical significance of the acoustic detection of coronary artery stenosis,” *J Cardiol.,* vol. 38, no. 5, pp. 255-62, 2001.
[27] Y. Akay, M. Akay, W. Welkowitz, S. Lewkowicz, Y. Palti, “Dynamics of sounds caused by partially occluded femoral arteries in dogs,” *Ann. Biomed. Eng.,* vol. 22, pp. 493–500, 1994.
[28] V. Padmanabhan, J. Semmlow, W. Welkowitz, “Accelerometer type cardiac transducer for detection of low level heart sound,” *IEEE Trans. Biomed. Eng.,* vol 40, pp. 21–28, 1993.
[29] J. Wang, B. Tie, W. Welkowitz, J. Semmlow, J. Kostis, “Modeling sound generation in stenosed coronary arteries,” *IEEE Trans. Biomed. Eng.,* vol. 37, pp. 1087–1094, 1990.